FINAL REPORT

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Accomplishments Under ARM Support

In this report are summarized our contributions to the Atmospheric Measurement (ARM) program supported by the Department of Energy. Our involvement commenced in 1990 during the planning stages of the design of the ARM Cloud and Radiation Testbed (CART) sites. We have worked continuously (up to 2006) on our ARM research objectives, building on our earlier findings to advance our knowledge in several areas. Below we summarize our research over this period, with an emphasis on the most recent work.

1. IOP Research Activities

We have participated in several aircraft-supported deployments at the SGP and NSA sites. In addition to deploying the Polarization Diversity Lidar (PDL) system (Sassen 1994; Noel and Sassen 2005) designed and constructed under ARM funding, we have operated other sophisticated instruments (W-band polarimetric Doppler radar, and midinfrared radiometer for intercalibration and student training purposes. We have worked closely with University of North Dakota scientists, twice co-directing the Citation operations through ground-to-air communications, and serving as the CART ground-based mission coordinator with NASA aircraft during the 1996 SUCCESS/IOP campaign. We have also taken a leading role in initiating case study research involving a number of ARM coinvestigators. Analyses of several case studies from these IOPs have been reported in journal articles, as we show in Table 1. The PDL has also participated in other major field projects, including FIRE II and CRYSTAL-FACE.

Table 1: SGP CART Cloud IOP Analyses

IOP	Date	Subject	Reference
Spr 1994	18 Apr	Citation contrail case study	Sassen 1997
	19 Apr	Cold cirrus case study	Sassen et al. 1998
	21 Apr	Melting layer case study	Sassen and Chen 1995
	30 Apr	Stratus cloud retrieval	Sassen et al. 1999
	30 Apr	Stratus cloud retrieval	Mace and Sassen 2000
	30 Apr	Stratus ozone depletion	Wang and Sassen 2000
Spr 1996	Various	Lidar contrail observations	Sassen and Hsueh 1998
	24 Apr	Cirrus cloud retrieval	Mace et al. 1998
Fal 1997	26 Sep	Cirrus cloud retrieval	Sassen and Mace 2002
	26 Sep	Cirrus cloud retrieval testing	Wang and Sassen 2002a
	26 Sep	Nora cirrus case study	Sassen et al. 2003a
	27 Sep	Altocumulus case study	Wang et al. 2004
Spr 1998	Various	Central American smoke pall	Peppler et al. 2000

Fal 2004	17 Oct	M-PACE cirrus case study	Under preparation
	Various	M-PACE design and studies	Verlinde et al. 2007

In general, the published results of our IOP research can be divided into two categories: comprehensive cloud case study analyses to shed light on fundamental cloud processes using the unique CART IOP measurement capabilities, and the analysis of in situ data for the testing of remote sensing cloud retrieval algorithms. One of the goals of the case study approach is to provide sufficiently detailed descriptions of cloud systems from the data-rich CART environment to make them suitable for application to cloud modeling groups, such as the GEWEX Cloud Simulation Study (GCSS) Cirrus Working Groups. We summarize our IOP-related accomplishments below.

i) Cirrus Cloud IFO Research

A great amount of effort has gone into analyzing the properties of midlatitude cirrus over the CART site. A detailed analysis of the 19 April 1994 subtropical cirrus case study was reported in Sassen et al. (1998). Its significance lies in the unusually cold (-60° to -71°C) and high (10-14 km) cloud properties for midlatitude cirrus. The cirrus generated a lunar corona display indicative of very small ~20 um particles, as was confirmed with *in situ* FSSP measurements. The small particles and uncertain ice crystal nucleation processes are of interest to the modeling community. Khvorostyanov and Sassen (2002) reported 2D model findings designed to reproduce the IOP data, indicating that the homogeneous freezing of sulfuric acid droplets (Bodgen et al. 2006) were probably important in generating this tropopause-topped cirrus layer.

An unusual cirrus cloud event that occurred on 26 September 1997 was described in detail in Sassen et al. (2003a). The cirrus were derived from hurricane Nora, which developed in the unusually warm El Nino waters off the Baja coast. As it weakened and dissipated over southern Arizona, its huge cirrus cloud shield was advected over the Southwest, where it was studied at FARS in Salt Lake City on 25 September, and then was redirected over the SGP CART site the next day during an IOP. A rare property of this high cloud system was that it generated spectacular optical displays both over SLC and the SGP CART site, including 22° and 120° parhelia and a parhelic circle. Considering that ice crystal residence times in a particular cirrus do not typically exceed several hours, this indicates a continuous regeneration of those ice crystal types responsible for the display, which we speculated were due to the formation of ice crystals from sea salt nuclei lofted by hurricane-force winds up to 60 m s^{-1}. Interestingly, DRI ice particle replicas sometimes reveal circular and irregular features at the centers of ice crystal casts that strongly resemble marine microbes, indicating that plankton can serve as biogenic ice nuclei (see Figure 1). The *in situ* data have also been applied to testing combined lidar and radar retrieval algorithms to determine cirrus ice water content IWC, effective size, and radiative properties (Sassen 2002a; Wang and Sassen 2002a). Clearly, this intensively studied case offers an excellent opportunity to research the maintenance of midlatitude cirrus, and may be taken up by the GCSS Cirrus Working Group 2 as a cirrus dataset to be simulated in the 2D cloud model intercomparison project.

More recently, the PDL participated in the September-October 2004 Mixed-Phase Cloud Experiment (M-PACE) conducted in and around the NSA site. Although the laser and power supply suffered serious damage during shipment by barge to Barrow, the system was repaired, albeit with considerably reduced output power. Unexpectedly, during the final week of the campaign cirrus clouds were prevalent. The PDL captured several of these Arctic cirrus cloud events at unparalleled (up to 0.1-s time and 1.5-m range) resolutions, and at two laser wavelengths (1.06 and 0.532 μm). Of particular interest is the 6-km deep cirrus cloud system that was studied by the PDL and M-PACE project aircraft on 17-18 October. The cloud initially more resembled midlatitude cirrostratus cloud with cloud tops of 10.5 km MSL, but these heights later dropped to ~6.0 km in what resembled a low-level cirrus radiatus cloud system. Thin supercooled liquid altocumulus clouds were embedded in these clouds, one of which with a temperature approaching the -40°C temperature level (Verlinde et al. 2007).

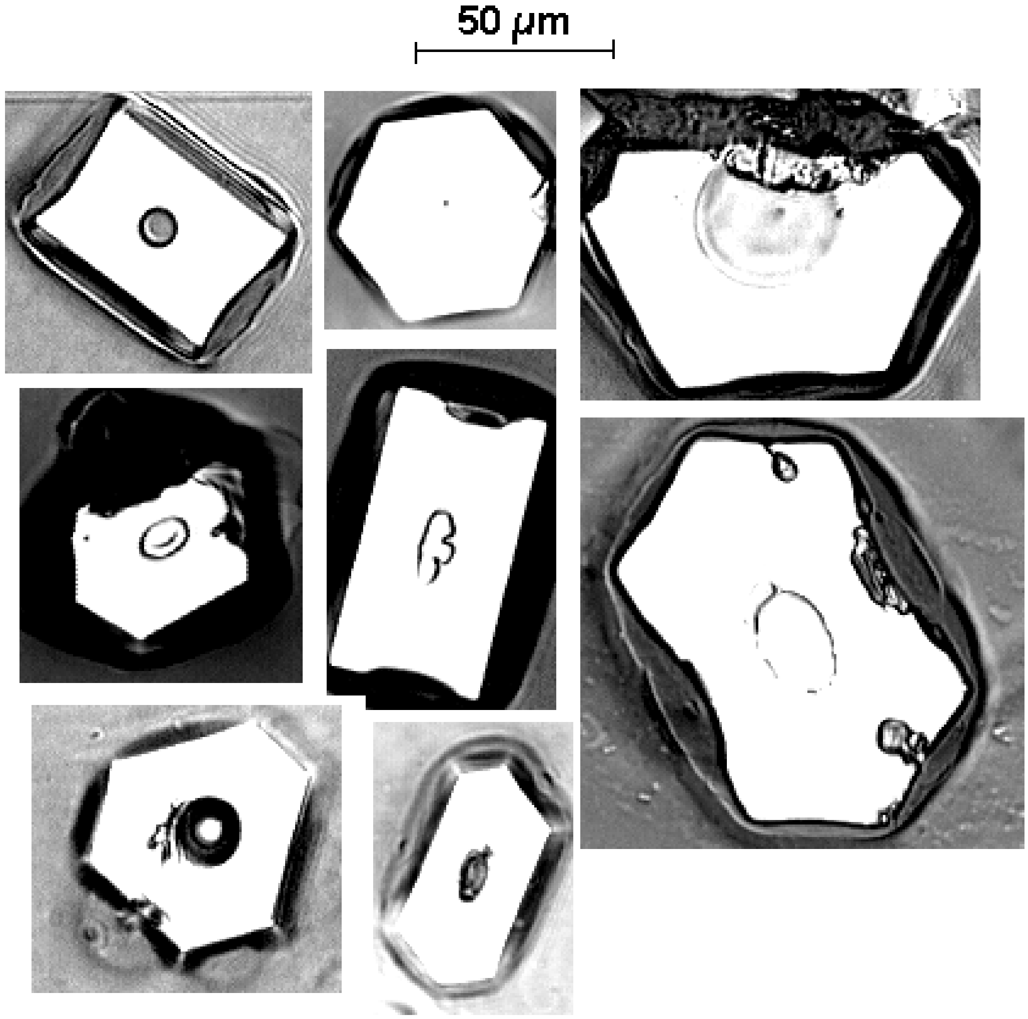

Figure 1. Ice crystal replicas from the hurricane Nora cirrus case study collected over the SGP CART site on 27 September 1997, showing central designs resembling marine microbiota that apparently served as ice nuclei. Note size scale at top.

ii) Aircraft Condensation Trail (Contrail) Research

A special flight pattern was designed that allowed the Citation aircraft to both generate and then sample its own contrail: on 18 April 1994 it was conducted after cirrus clouds had vacated the CART site. The PDL and in situ data were reported in a review article of contrail properties (Sassen 1997), representing a uniquely comprehensive contrail study at that time. Note that a parameterization of the contrail ice particle size distribution derived in this case.and from the 19 April 1994 cirrus, have been used in the radiative transfer study of Liou et al. (1998), and the mean contrail particle sizes to help validate the 2D model predictions in Khvorostyanov and Sassen (1998a).

The combined Cloud Remote Sensing IOP/SUCCESS campaign during spring 1996 provided several opportunities to research contrails and the contrail-cirrus clouds derived from spreading contrails. In Sassen (1997), scanning PDL measurements of a young NASA DC-8 contrail were given, illustrating the structure of a new contrail with evolving particle sizes and shapes, and lidar linear depolarization ratios, or δ-values (Mischenko and Sassen 1998). An exploration of the laser scattering and depolarization properties of both young and old, sometimes subvisual, contrails were presented in Sassen and Hsueh (1998). The range of contrail δ-values was quite large, but were often much larger than the background cirrus, indicating distinct ice particle shapes.

iii) Stratus Cloud Research

The 30 April 1994 continental stratus cloud case study has yielded a number of articles. Although marine stratus clouds have received scientific scrutiny in projects such as FIRE and ASTEX, their continental counterparts have not been rigorously studied with the aid of modern instrumentation. Thus an analysis of this case study using the PDL, U. Mass. CPRS (k-band Doppler radar), CART dual-channel microwave radiometer MWR, and the 3-h supporting Citation aircraft mission, coupled with our newest algorithms, obtained a unique high-resolution image of the stratus cloud properties (Sassen et al. 1999). Using the radar liquid water content LWC algorithm developed earlier in our ARM program (Liao and Sassen 1994; Sassen and Liao 1996), the radar reflectivities were converted to LWC fields and liquid water path LWP, and a new algorithm was used to derive the vertical profile of effective droplet radius (*r*).

Our approach relies on regression analysis of adiabatic cloud model simulations to predict the relation between equivalent radar reflectivity factor Z_e ($mm^6\ m^{-3}$) and LWC ($g\ m^{-3}$), depending on the droplet concentration N_d (cm^{-3}):

$$Z_e = (3.6/N_d)\ LWC^{1.8} \quad . \tag{1.1}$$

However, the reliance of this method on knowledge of N_d is overcome through the use of coincident LWP information provided by the MWR. From Eq. (2.1) and the definition of LWP, we have

$$N_d = 3.6\ (LWP\ /\ \Delta z)^{1.8}\ \ /\ \Sigma\ \ Z_e \quad , \tag{1.2}$$

where Δz is the cloud physical depth and the summation of Z_e is over the cloud base to cloud top heights.

Finally, with knowledge of the radar-derived LWP and N_d, it is straightforward to compute a measure of the mean cloud droplet radius using the following definition,

$$r = (3\,LWC/4\pi\rho\,N_d)^{1/3} \quad . \qquad (1.3)$$

We have also shown that even the width of the cloud droplet spectra can be derived using this method (Mace and Sassen 2000). In terms of *in situ* data "validation", the aircraft data were in reasonable agreement, although it was suggested that some differences resulted from the inability of the FSSP to detect the small number of the largest droplets present that the radar, with its considerably larger scattering volume, could detect (Sassen et al. 1999).

The IOP data from this occasion were also used to test a hybrid algorithm to derive stratus cloud microphysical properties using solar radiation, microwave radiometer, and cloud radar data (Mace and Sassen 2000). Because current stratus cloud algorithms are adversely affected by the presence of drizzle, ice crystals, or insects, we also offered an equation to allow the identification of such non-adiabatic conditions in radar returns. We accomplished this via 1D cloud model simulations to, in effect, predict the slope in Z_e that would occur due to the basic adiabatic growth (i.e., increases in size and LWC with height) of the droplets above cloud base. The following parameterization in terms of the approximate stratus cloud base temperature T (°C, derived from radiosonde or infrared radiometer data) provides a test to determine if the proper conditions are met to apply an algorithm:

$$10\,\mathrm{Log}\,(Z_e) = -70.06 + 0.303T - 0.00593\,T^2 + (19.697 + 0.0182T + 0.000238\,T^2)\,\mathrm{Log}\,(H) \quad , \qquad (1.4)$$

where H is the height (m) above the (lidar-detected) cloud base position. The curves generated by this equation provide the maximum Z_e that can be generated adiabatically at any H, such that if Z_e along the profile is exceeded significantly, or the signal slope is incompatible, it is assumed that *additional* scatterers (precipitation or insects) are present and the algorithm is not applied.

Finally, in Wang and Sassen (2000) is given the first evidence from Citation data, in and surrounding the stratus, that the cloud layer was responsible for significant ozone depletion, in support of previous theory.

iv) Precipitating Cloud Research

The 21 April 1994 case study of light rain showers produced by descending anvil clouds resulted in the first report of the existence of the lidar "dark" band (Sassen and Chen 1995). It was deduced using PDL, 95 GHz Doppler radar, and *in situ* data that the conspicuous lidar scattering minimum at the bottom of the snowflake melting region was due to the ice-containing raindrops created by the collapse of melting snowflakes, which blocked the backscattering of light from the rear droplet surface. This has been more recently confined by combine lidar and triple-wavelength Doppler radar data collected during the CRYSTAL-FACE field experiment (Sassen et al. 2005), where the PDL was operated.

b. Other Cirrus Cloud Research

Cloud Polarization Lidar (CPL) cirrus data (Sassen 2002b, 2005b) from the new University of Alaska Fairbanks Arctic Facility for Atmospheric Remote Sensing (AFARS, formerly the University of Utah FARS) and Micropulse Lidar (MPL) data from NSA (Tiruchirapalli 2006) have revealed that during the winter-spring seasons, particles from Asian dust storms are regularly present above Alaska. Because of the persistence of the Arctic weather front for much of the year, and thus the usual lack of major air mass exchanges with midlatitudes, the winter environment is generally pristine with remarkably low aerosol mass loadings. Those injections of midlatitude air with significant aerosols or pollutant gases (e.g., sulfur compounds that lead to Arctic haze) that do occur can be traced back to their general source region through backtrack analysis using global wind sounding data. Once injected into the Arctic by certain weather patterns off the coasts of Alaska or Iceland, for example, we have noted that the air masses tend to slowly recirculate, and that the aerosol laser backscattering slowly diminishes with time (presumably due to loses associated with cloud particle formation and scavenging). Importantly, we have found evidence that Asian dust particles acted as efficient deposition ice nuclei, which formed ice crystals in the dust layers directly from the vapor phase at temperatures between -20° to -40°C, and in air just above ice saturation (see Figure 2). These environmental properties can be far warmer and drier than those associated with cirrus cloud formation, as we have pointed out in a recent article in *Nature* (Sassen 2005b).

Dr. Likun Wang recently completed his Ph. D. dissertation at UAF, entitled, *Midlatitude Cirrus Cloud Structural Properties Analyzed from the Extended Facility for Atmospheric Remote Sensing Dataset* (2004). This research is based on the analysis of a 10-year cirrus cloud lidar dataset (from the former FARS) using wavelet, autocorrelation, and other statistical methods, to identify and characterize the structures within cirrus clouds. This knowledge is critical to improving the radiative transfer treatment of realistic layer clouds, because it is well known that the plane-parallel homogeneous assumption, and other model simplifications, can lead to significant errors in radiative calculations (e.g., Carlin et al. 2002; Liou et al. 2002). One approach has been to employ wavelet analyses as a function of height within cirrus to identify periodic structures and characterize their wavelengths using radiosonde wind data and laser backscattering profiles in relatively optically thin (<~2.0) clouds. The presence of cirrus mammatus at cloud base was surprisingly frequent, and may be important to the turbulent kinetic energy budget of the middle/upper atmosphere (Wang and Sassen 2006; Sassen et al. 2007). Analyzes were also begun include detailed studies of the uncommon Kelvin-Helmholtz waves, and the common cloud-top cirrus uncinus cells along with their mesoscale cloud organizations into Mesolscale Uncinus Complexes, or MUC (Sassen et al. 1989).

The other avenue of research using this extended dataset is climatological in nature for direct application to large-scale models. Wavelet analyses of individual cirrus cloud systems combined into a single dataset reveal that Kelvin-Helmholtz waves, cirrus mammata, and uncinus cells (all with wavelengths of ~1-10 km), as well as longer mesoscale cloud organizations, represent ~8.4%

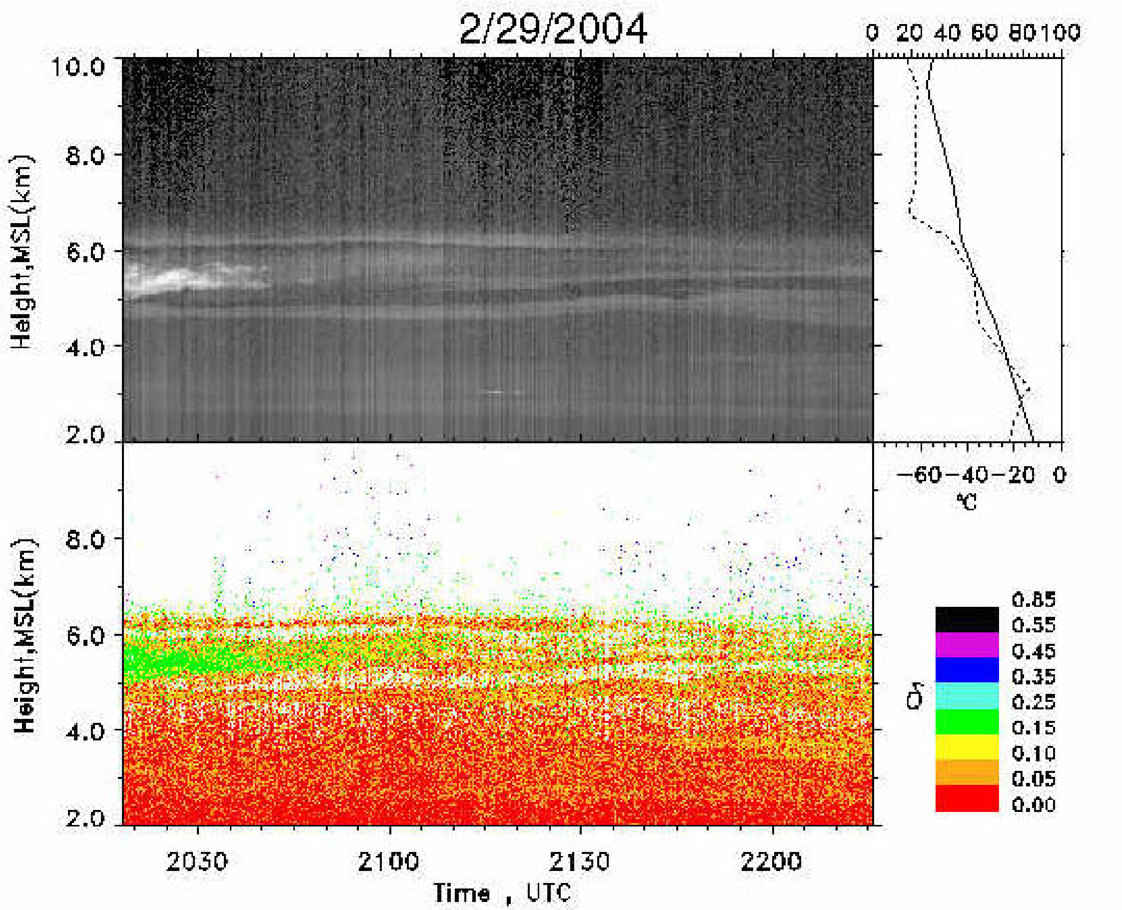

Figure 2. An example of polarization lidar capturing an apparent Asian dust aerosol indirect effect on the formation of an ice cloud via the depositional ice nucleation mechanism, from AFARS on the indicated date.

(18.8%, 30.8%) of the total data after passing a 95% (75%, 50%) confidence level test. Using integrated backscattering as a proxy to examine cloud optical depth variability, we find a steady decrease in autocorrelation coefficients starting at a few kilometers as the length (or model grid) scale increases. In other words, most cirrus cloud organizations tend to be aperiodic, and there are no preferred wavelengths for cloud-scale or gravity wave-induced mesoscale cloud features. We have concluded that midlatitude cirrus clouds are inherently inhomogenous, and that this reality must be accounted for in modeling the radiative transfer through simulated cirrus clouds through subgrid-scale parameterizations.

c. Empirical Remote Sensing Algorithm Development Using Datasets

The usual method for developing cloud retrieval algorithms relies on converting *in situ* or ground-based datasets into remotely-sensed data quantities. This empirical approach has a long history, particularly with the determination of precipitation rate using radar. We have used this approach previously for developing radar-only algorithms for IWC, such as IWC = 86.3 $Z_e^{0.83}$ (from Sassen and Liao 1996), but such simple (one-parameter) approaches have their limitations (see below).

More recently, we have developed two, more sophisticated algorithms using extensive multi-year multiple remote sensor datasets from the SGP CART site. The first relies on lidar, radar, microwave radiometer, and infrared brightness temperature data to allow the identification of the eight major cloud types from the CART data stream (Wang and Sassen 2001). Inherent in this scheme is the identification of cloud boundaries, phase, and precipitation, and distinguishing between cloud and aerosol layers. We have made available our code for incorporation into the SGP CART value-added data products data stream. These activities continue with the collaboration of (former student) Prof. Zhien Wang, and early results for mixed phase clouds at the NSA site were recently reported at the 2005 annual STM. We have also participated in a IWC algorithm intercomparison project (based on IOP measurements) using our radar-only and radar plus lidar algorithms (Comstock et al. 2007).

The second algorithm uses combined CART Raman lidar and MMCR millimeter radar data to obtain IWC and effective ice particle size in cirrus clouds (Wang and Sassen 2002a). Using additional parameterizations, it also allows the estimation of cirrus cloud visible extinction (Sassen et al. 2002) and infrared absorption coefficients (Wang and Sassen 2002b). Thus, this algorithm generates cirrus cloud ice water path IWP, visible optical depth τ, and infrared layer emittance ε, the basic quantities typically needed to treat cirrus clouds in large-scale models. As indicated in Table 1, this approach has been tested favorably against *in situ* data collected at the CART site.

Finally, a new algorithm especially designed for dry Arctic atmospheric conditions uses combined active remote sensor and spectral infrared AERI data to retrieve the microphysical and macrophysical properties of mixed phase clouds (Wang et al. 2004).

d. Remote Sensing Algorithm Development Using Models

In addition to relying on field data to help construct remote sensor-based cloud property retrieval algorithms, we have helped pioneer the approach of converting cloud microphysical model predictions into remote sensing and radiative data quantities. Both our parcel cloud model (Sassen et al. 1992) and 2D model (Khvorostyanov and Sassen 1998b) have been used for this purpose.

Parcel model results have been at the foundation of developing radar-only algorithms for LWC (Liao and Sassen 1994; Sassen and Liao 1996), and the retrieval of LWC and mean drop radius using combined radar and microwave radiometer data (Sassen et al. 1999). This model was also used to determine the feasibility of parameterizing the effects of both homogeneous and heterogeneous ice nucleation processes in cirrus clouds, as explored in Sassen and Benson (2000). Finally, simulations of liquid-phase supercooled altocumulus clouds at various temperature has led to the parameterization of τ and ε for these midlevel clouds (Sassen et al. 2001a).

More recently, we have used the 2D cloud model to test cirrus IWC retrieval algorithms based on millimeter-wave radar reflectivity Z measurements (Sassen et al. 2002). The simulated ice particle size spectra over a 12-h growth/dissipation life cycle were converted to Z and visible optical extinction coefficients, which were used as a test dataset to intercompare the results of available algorithms. We showed that radar Z-only approaches suffer from significant problems related to basic temperature-dependent cirrus cloud microphysical processes, although most algorithms worked well under limited conditions (presumably similar to those of the empirical datasets from which each was derived). However, the results were improved using multi-parameter algorithms, most notably the lidar/radar algorithm of Wang and Sassen (2002a), and a new relation based on a cirrus cloud-top temperature T_{ct} correction factor. We continue to participate in ARM Cloud Properties Working Group algorithm intercomparison projects to test new insights.

Both our parcel (Lin et al. 2002) and 2D cloud models have participated in recent GEWEX model comparison projects designed to improve the simulation of cirrus clouds.

e. Cirrus Cloud Parameterizations

In attempting to derive improved cirrus cloud microphysical and radiative parameterizations, we have relied on both extended datasets collected at the SGP CART site, and the 14-year record of lidar and radiometer data from FARS (funded by NSF and NASA). Using FARS data and the combined lidar and infrared radiometer (LIRAD) method (Platt 1979; Comstock and Sassen 2001), we developed parameterizations of τ and ε in terms of cloud physical thickness and midcloud temperature for both cirrus and altostratus clouds (Sassen et al. 2001). These relationships were further stratified by the cirrus source (i.e., synoptic, anvil, and orographic) in Sassen and Comstock (2001), revealing some interesting differences.

Returning to the analysis of extended lidar/radar and LIRAD cirrus data from the FARS and SGP CART sites, we have derived new and improved parameterizations of the visible extinction coefficient σ_e (km^{-1})

$$\sigma_e = 0.49 + 0.0052\ T_m. \quad (1.5)$$

and the infrared absorption coefficient σ_a (km^{-1})

$$\sigma_a = 0.2896 + 3.409 x 10^{-3}\ T_m \quad (1.6)$$

where T_m is the midcloud temperature (°C). In Sassen et al. (2002b) we were able to reconcile the previous parameterizations developed using the LIRAD method (Platt and Harshvardhan 1988; Comstock and Sassen 2001) with our lidar/radar algorithm by pointing out differences used in the manner of data curve fitting, and the composition of the cloud samples.

f. SCM/GCM Cirrus Cloud Parameterizations

With the collaboration of V. I. Khvorostyanov of the Moscow Aerological Observatory, a 2D version of a 2D/3D cloud model complex with explicit microphysics and radiation was modified for a more complete account of processes in cirrus clouds (Khvorostyanov and Sassen 2002). A new element incorporated into the model included an improved homogeneous nucleation theory (Khvorostyanov and Sassen 1998d). A number of distinct atmospheric cases were simulated to correspond to diverse midlatitude cirrus conditions. Numerous numerical experiments were performed in order to reproduce the cirrus life cycle, to understand the role of various factors in cirrus formation, and to test the sensitivity to the initial conditions, mechanisms of nucleation, and radiative interaction. Many simulations have been based on comprehensive SGP cloud case studies (Khvorostyanov and Sassen 2002).

We found that the process of vapor deposition to cirrus ice crystals is far from instantaneous. Rather, it is determined by the deposition time τ_{fc} which represents the characteristic time of crystal super-saturation absorption. In contrast to liquid clouds where τ_f are typically 1-10 s, the condensation time in cold ice clouds varies from ~0.5 to >5 h, and depends on the nucleation process. As a result, IWC is comparable to or significantly less than the amount of uncondensed excess vapor, and the evaporated ice in the subsaturated layer is much less than the subsaturation. Since many bulk cloud models and GCMs transform the entire vapor excess in a few time steps (i.e., 5-10 min), or in a characteristic model time of about 1-h, this procedure can overestimate by a factor of two or more the IWC, optical thickness, emissivity, latent heat, etc.

In terms of cloud radiative properties, experiments and theoretical investigations have produced quite different (from ~100-3500 cm^2/g) values for the longwave mass absorption coefficient. Our model results indicate that a single representative absorption coefficient is inappropriate. There is generally a 3D field of values that depends on the precise cloud microstructure, and so determines the cooling/heating rates. Similar 3D fields of the visible scattering coefficient determine the optical properties in the solar spectrum. It appears that many GCM and climate models rely on unrepresentative values for these coefficients, which are greater than seem to be appropriate for typical cirrus, and constant with height. A comparison of the radiative fluxes calculated with the optical coefficients produced by this model and with those typically used in GCMs has shown that the use of the latter can lead to a significant increase in the LW and SW radiative fluxes (by 30-100 W m^{-2}). The cooling in the upper part of the cloud and the heating in the lower part are both strongly enhanced. Such approaches imply an unjustifiable increase in the static instability and cirrus cloud convective activity in the upper troposphere.

Based on the results of these extensive numerical simulations, a number of specific recommendations for SCM/GCMs or cloud bulk models were developed, as described in Khvorostyanov and Sassen (2002).

g. Student and Post-Doctoral Appointment Training

Former students, Jennifer. M. Comstock (Ph. D.), Sally Benson (M.S.), Zhien Wang (Ph. D.), Likun Wang (Ph. D. at UAF)) and Ramaswamy Tiruchirapalli (M.S. at UAF) were at least partially supported by ARM funding since 2002, and have participated in IOPs for field research training purposes and obtaining data for thesis research. The dissertation of Z. Wang was in the area of multiple remote sensor cloud data analysis and algorithm development, which he continued to pursue as a DOE-supported Post-Doc. Post-Doc Diana Daneva most recently worked on developing mix-phase cloud property retrieval algorithms using polarization lidar data.

h. GEWEX Cloud Simulation Study (GCSS) participation

Since 1996, we have participated in the GCSS Work Group 2 on Cirrus Clouds using ARM funding in order to work towards improving large-scale model treatments of cirrus clouds. We continue to contribute to the parcel modeling (Lin et al. 2002) and 2D/3D modeling (with V. I. Khvorostyanov) activities meant to examine fundamental cloud processes and improve their parameterization *up the food chain* to GCMs. We have also worked to make available comprehensive case studies of cirrus cloud systems from various SGP IOPs to the modeling community.

i. Participation in ARM Working Groups

We have long participated in various ARM working groups to help define and overcome outstanding ARM CART instrument issues (e.g., low liquid water content clouds), and refine remote sensor-based cloud property retrieval algorithms (especially for identifying cloud type).

j. Collaborations

Over the past several years I have established valuable working relationships with other ARM program investigators, as evidenced by our journal article coauthorships (see below), which I expect to continue and enhance during the next ARM phase. In particular, I will collaborate with Dr. V. I. Khvorostyanov of the Central Aerological Observatory (Mossow) for Arctic 2D/3D cloud model simulations; K.-N. Liou of UCLA for inhomogeneous cloud radiative transfer research; former students Z. Wang (now at University of Wyoming) for joint VAP algorithm development and L. Wang (now at NOAA) for cirrus cloud structural analyses; G. Stephans and D. Winker for space-based CloudSat and Calipso satellite data retrieval methods; D. O'C. Starr for testing model simulations using lidar/radar data from CART campaigns within the GEWEX Working Groups; UND Citation scientist M. Poellet for continued aircraft data analysis. I also hope to work closely with NSA Site Manager B. Zak and others at the Geophysical Institute on matters relating to NSA site research.

k. Publications Acknowledging ARM Support

See the Bibliography, where over fifty reviewed journal articles and book chapters acknowledging our ARM support are identified.

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